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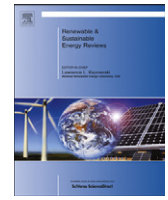

An analysis of wind power potential in Port Said, Egypt

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A B S T R A C T

Measurement station with mast of 19 m has been established in a built-up area, near the seashore to study the structure of a coastal location "Port Said" on Suez Canal–Mediterranean Sea intercept in Egypt. From our analysis of the wind data, an important characteristic is revealed in that the wind speed Spring months are more than that in Winter period. This characteristic is opposite to the prevailing wind speed parameters in most European countries. This paper also gives a detailed analysis of measured frequency distributions and monthly wind speed variation with air temperature that can exploited in the best way for fast wind machines.

A numerical model was introduced to calculate the monthly and annual average wind energy flux and found to be quite moderate (in excess of 92 kW/m^2 per year at 50 m hub height) for this area.

It appears from our research that the expected energy from the wind in Port Said region – which is nearly like an island – lies in the medium range. This potential can be converted to electrical energy specially in the Spring months. However, an immediate application seems to be limited to electricity generation using medium size wind farms and water pumping.

Contents

1. Introduction

Wind is the air movement caused by forces due to the Earth's rotation, buoyancy forces due to gravity and solar heating of the ground, and the resistance to the wind exerted by the Earth's surface. This resistance of the Earth's surface causes the wind speed to increase with height above the ground. The greatest changes in wind speed generally occur between the surface and a height of about 60 m. Currently, the world has a total of 238,000 MW of electricity generating capacity after a record 41,000 MW was installed by wind energy developers in 2011.The residential electricity needs of 380 million European consumers can now be satisfied since there is enough installed wind power. More than 80 countries are tapping wind energy [1].

Worldwide there are now many thousands of wind turbines operating, with a total nameplate capacity of 238,351 MW as of end 2011. World wind generation capacity more than quadrupled between 2000 and 2006, doubling about every three years. The United States pioneered wind farms and led the world in installed capacity in the 1980s and into the 1990s. In 1997 German installed capacity surpassed the U.S. and led until once again overtaken by

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the U.S. in 2008. China has been rapidly expanding its wind installations in the late 2000s and passed the U.S. in 2010 to become the world leader. At the end of 2011, worldwide nameplate capacity of wind-powered generators was 238 gigawatts (GW), growing by 41 GW over the preceding year. Regarding the wind data from the World Wind Energy Association for year 2010, an industry organization states that wind power now has the capacity to generate 430 TWh annually, which is about 2.5% of worldwide electricity usage. Between 2005 and 2010 the average annual growth in new installations was 27.6%. Wind power market penetration is expected to reach 3.35% by 2013 and 8% by 2018. Several countries have already achieved relatively high levels of penetration, such as 28% of stationary (grid) electricity production in Denmark (2011), 19% in Portugal (2011), 16% in Spain (2011), 14% in Ireland (2010) and 8% in Germany (2011). As of 2011, 83 countries around the world were using wind power on a commercial basis [2–6]. Europe accounted for 48% of the world total wind power generation capacity in 2009. In 2010, Spain became Europe's leading producer of wind energy, achieving 42,976 GWh. Germany held the top spot in Europe in terms of installed capacity, with a total of 27,215 MW as of 31 December 2010. In 2010, more than half of all new wind power was added outside of the traditional markets in Europe and North America. This was largely from new construction in China, which accounted for nearly half the new wind installations (16.5 GW).

Utilization of wind energy is well known in old Egypt from many centuries ago. It went back to third century B.C. where an evidence that ancient Egyptians used Windmills for grinding grain and pumping water from the Nile River, for irrigation purposes, does occur [7]. Nowadays, Egypt is a developing country, with a population of about 85 million inhabitants. There is a growing awareness for renewable energy resources in south Egypt as a result of the aim of Egyptian government for rapidly increasing population and industrial development at this region. Furthermore, Egypt does not possess enough fossil fuel reserves at deep south country, but possesses only in this area large resource for electricity generation hydropower (High Dam Aswan) [8].

The potential for wind depends on there being a good wind resource, on wind generation being sufficiently close to the transmission grid to allow economic connections to be made and on the fact that there are no other issues that preclude wind development (for example, radar communications close to military installations). Whether this wind potential can be developed economically depends on the costs of wind in comparison to alternatives. The New and Renewable Energy Authority (NREA) has done extensive work over the past 13 years, building a very comprehensive state-of-the-art wind atlas for Egypt in cooperation with Risoe National Laboratory. Fig. 1 shows an extract from the atlas, at a typical turbine hub height of 50 m above the surface. Areas in red, pink and purple are those where the power density is above 400, 500 and 600 W/m^2 respectively. The economics of areas in yellow (where the wind power density is 300–400 W/m^2) are marginal [9–11].

According to New and Renewable Energy Authority of Egypt (NREA), Egypt has planned major short- and long-term extensions to its wind capacity for many years. The short term extensions pass through two phases. The first phase (2008–2012) is nearly finished. Capacity additions are planned to average 200 MW per

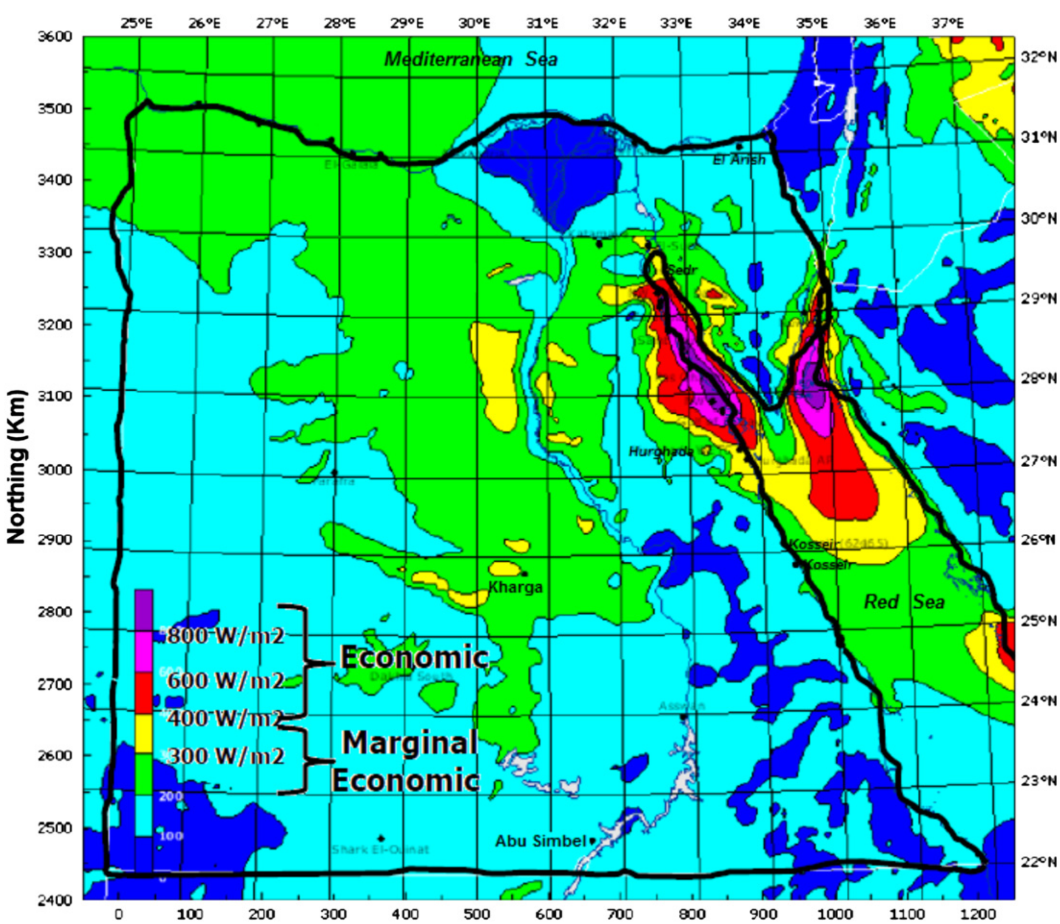

Fig. 1. Wind atlas for Egypt (power density at 50 m, in W/m^2) after NREA, 2008. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Table 1
Tentative time schedule for additional wind farm capacities in Egypt, after NREA, 2008.

Year		2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
New capacity (MW)	**NREA private**		320	220 120	500	500	750	900	900	1000	1000	1000	1000
Total MW		550	870	1210	1710	2210	2960	3860	4760	5760	6760	7760	8760

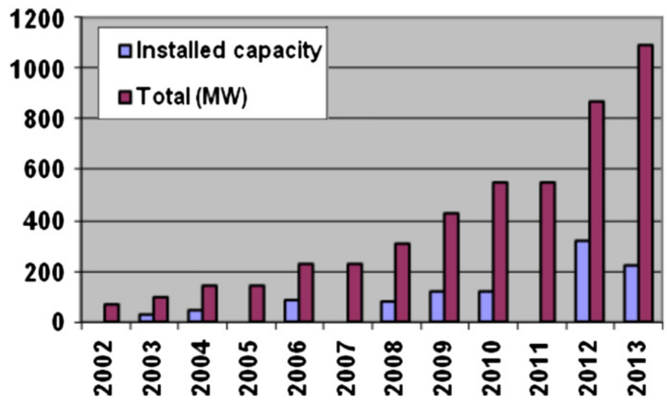

Fig. 2. Long-term chart for additional wind farm capacities in Egypt, after NREA, 2008.

year, with finance from overseas donor agencies. The second phase (after 2012), when private-sector developments are expected to add anywhere between 400 and 1000 MW of new capacity per year. The long-term plan is suggested in April 2007, when the Supreme Council of Energy (SCE) elaborated on a plan to increase the share of wind energy such that it would represent 12% of total electricity demand in the 2020–2021 fiscal year. This would require wind capacity to reach 7500 MW by 2020, as shown in Table 1 and Fig. 2. Were such a plan to be realized, Egypt would become one of the major wind users in the world [9–11].

The new energy sources should of course be “clean and renewable”. Solar and wind energy have these features and offer attractive alternatives. These sources are freely available, solar being limited only by latitude, time of year, cloud cover and atmospheric turbidity, while wind power is limited by season, time of day and the physical features of the area (topography) which may obstruct the flow of air [12,13]. This means that it depends on the site characteristics, so its variability is stronger in a country such as Egypt with its long coastline. Wind energy is an indirect form of solar energy and meteorologists estimate that about 1% of the incident solar radiation is converted into wind energy which is a very competitive source of energy for many applications in many locations. A few studies [14–21] presented the wind characteristics and its utility for some locations along the coast of Mediterranean Sea in Egypt.

This note presents a first analysis of wind data for Port Said region on the coast of Mediterranean Sea in Egypt, and provides a basis for a preliminary evaluation of wind power potential in the region.

2. Topography and wind data of the site

The wind speed behavior of a region is a function of altitude, season and hour of measurements. In this study, wind speed data, measured as hourly time-series in meteorological station at Port Said City, were statistically analyzed. Fig. 3 indicates the location of the station on the coast of Mediterranean Sea, which is along the broad coast of Suez Canal–Mediterranean intercept, where its grid coordinates are (31°16′N; 32°17′E) and elevation is one meter above the ground level. This zone is characterized by a wide flat coastal area along the sea and so the roughness factor in this research will be taken as constant after investigation, because the coast of Mediterranean Sea in the country is flat and homogeneous.

The wind speed frequency distribution at a given location is either tabulated from wind speed data as a function of time or is approximated by a probability distribution function based on measured data or assumed wind resources characteristics. It is important to know the number of hours per month or per year during which the given wind speeds occurred [22]. Ten years is the minimum time where one can get a reasonable mean value in a given site. Measurements of meteorological data were carried out at Port Said area for a period of more than 10 years by the Egyptian Meteorological Authority. The measured data over the period 1991–2005 was examined. The meteorological station is characterized by sandy and flat surface and is homogeneous. The measurements were determined with height of anemometer 19 m above the ground level. Monthly mean wind speed with its percentage frequency distribution from all directions are presented in Table 2. This table indicates that

(1) At Port Said station the wind blows from 360°N (wind direction), i.e. the wind in Port Said are predominantly northerly.
(2) The mean wind speed during September 3.8 m/s has the highest frequency occurrence during the year (35.7%), followed by (33.5%) for mean wind speed 4.6 m/s at June, followed by (31.2%) at 4.8 m/s during May.
(3) So, during these months peaks of mean wind speeds occur at different days with an average 3.8–4.8 m/s which is above the cut-in values required for the operation of any wind turbine in Egypt.
(4) Since the minimum required wind speed for a wind park (at 20 m height) is about 3 m/s which is equivalent to 2.54 m/s at 10 m height, atypical turbine will operate about 75–80% of all the time throughout the year [23].

Wind speed time series and air temperature observed for all months over the year are illustrated in Fig. 4. It is obvious from the comparison of these two time series that wind speed is more persistent with high scale in Spring season. But in Summer and Autumn periods sudden changes due to the noticed increase of air temperature during the months from June to October throughout the year.

An integral view of Fig. 4 gives the following findings:

(1) Port Said’s wind climate is characterized by the trade winds during Spring, where highest values measured of mean monthly wind speed occurred in Spring season. This can be explained by the weather phenomena of land and sea breezes. Where Port Said region is specified by the broad coast of Suez Canal–Mediterranean intercept and Lake of El-Manzala which is found to the east and south of the station. This means that Port Said City is nearly like an island.

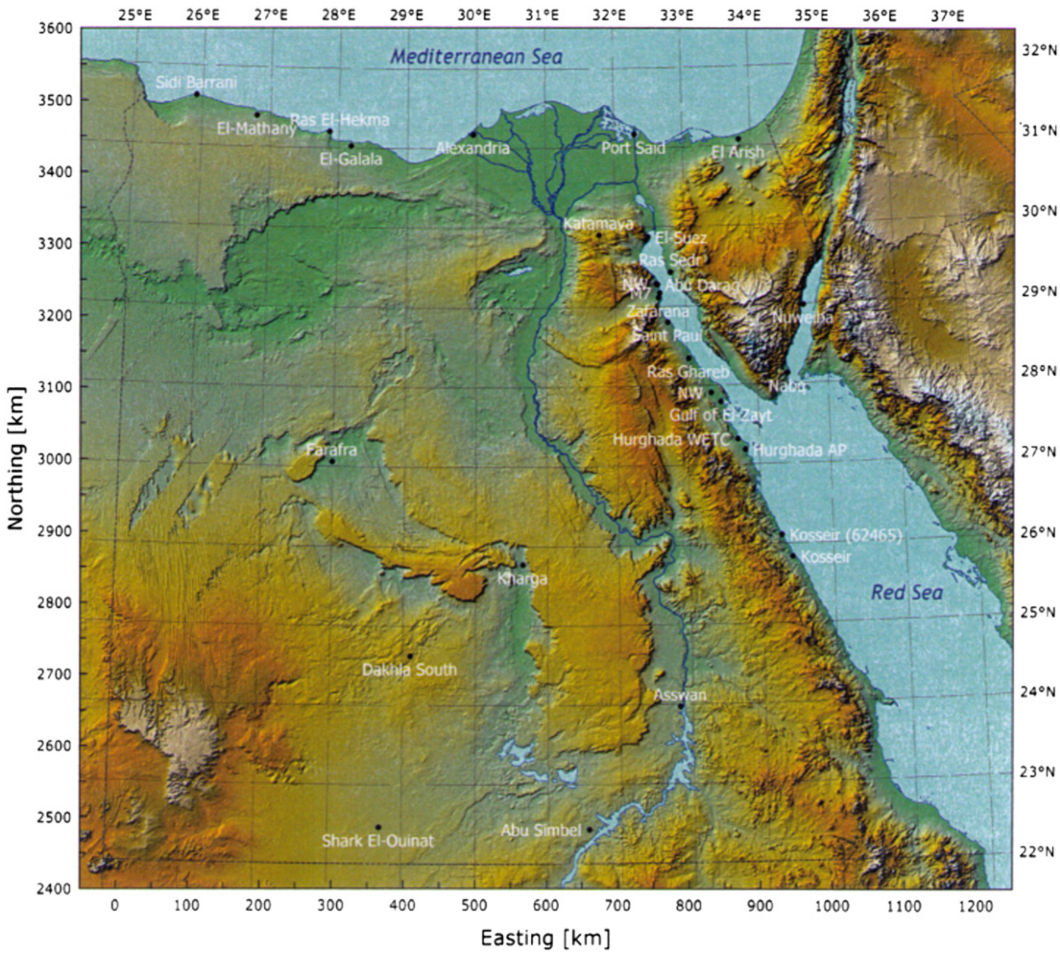

Fig. 3. The location of Port Said station along Mediterranean Sea in Egypt.

Table 2
Measured monthly mean wind speed and its percentage frequency distributions (at a height of 19 m).

Month	Mean wind speed	Percentage frequency of winds blowing from the following directions												
		N	NNE	ENE	E	ESE	SSE	S	SSW	WSW	W	WNW	NNW	Calm
January	4.8	4.5	5.1	6.8	5.8	3.9	4.5	7.4	14.1	19.5	14.9	6.0	4.9	1.0
February	5.2	9.2	9.3	9.9	8.0	4.2	2.9	4.1	6.8	14.0	14.0	7.6	8.5	0.7
March	5.8	11.0	9.9	11.5	9.7	3.8	2.9	3.3	3.8	8.8	14.7	9.3	10.3	0.6
April	5.4	19.9	12.5	12.8	9.1	3.4	1.9	1.7	1.8	4.1	8.1	3.4	15.6	0.4
May	4.8	31.2	15.6	10.6	7.5	2.9	1.5	1.0	1.2	3.0	5.4	5.9	13.6	0.4
June	4.6	33.5	9.0	4.3	2.5	1.4	1.1	0.6	1.2	3.0	7.7	10.9	24.3	0.3
July	4.3	26.5	4.0	0.9	0.4	0.3	0.4	0.2	0.5	3.9	15.3	16.1	30.7	0.4
August	3.8	27.3	4.7	0.7	0.3	0.3	0.3	0.3	0.9	4.1	15.3	13.4	31.3	0.7
September	3.8	35.7	11.2	2.9	0.8	0.5	0.5	0.4	0.6	3.3	8.3	6.9	27.5	0.7
October	4.1	25.2	20.5	11.4	3.7	1.6	1.8	1.3	2.1	4.8	7.4	5.7	13.8	0.4
November	4.3	16.2	17.9	14.2	3.8	1.6	1.5	2.7	5.1	8.7	10.8	6.4	9.8	0.7
December	4.3	5.5	8.6	8.5	6.3	4.1	4.1	6.6	14.4	18.9	10.6	4.8	4.9	1.3
Annual mean	4.6	20.5	10.7	7.9	4.8	2.3	2.0	2.5	4.4	8.0	11.0	8.4	16.3	0.6

(2) From January to May, strong trade winds come from north. And from July to October wind direction suddenly change accompanied by a drop in average wind speed.
(3) The maximum value is recorded at Port Said station with 5.8 m/s at 19 m height during March. A minimum value of recoded air temperature was 14.2 and 14.7 °C in January and February, respectively (Winter months).
(4) Annual average of air temperature at Port Said City during the year was 21.1 °C.
(5) Judging by the wind availability throughout the Autumn season, one can eliminate the utilization of wind energy in space cooling applications in Egypt. This disadvantage can be overcome by storing the excess power generated by the Spring wind.

3. Analysis method

As mentioned above to study the structure of the coastal wind field on Port Said region, wind speed recording instruments are located at 19 m height above the ground level by the Renewable Energy Authority in Cairo, Egypt. This means that the quality of

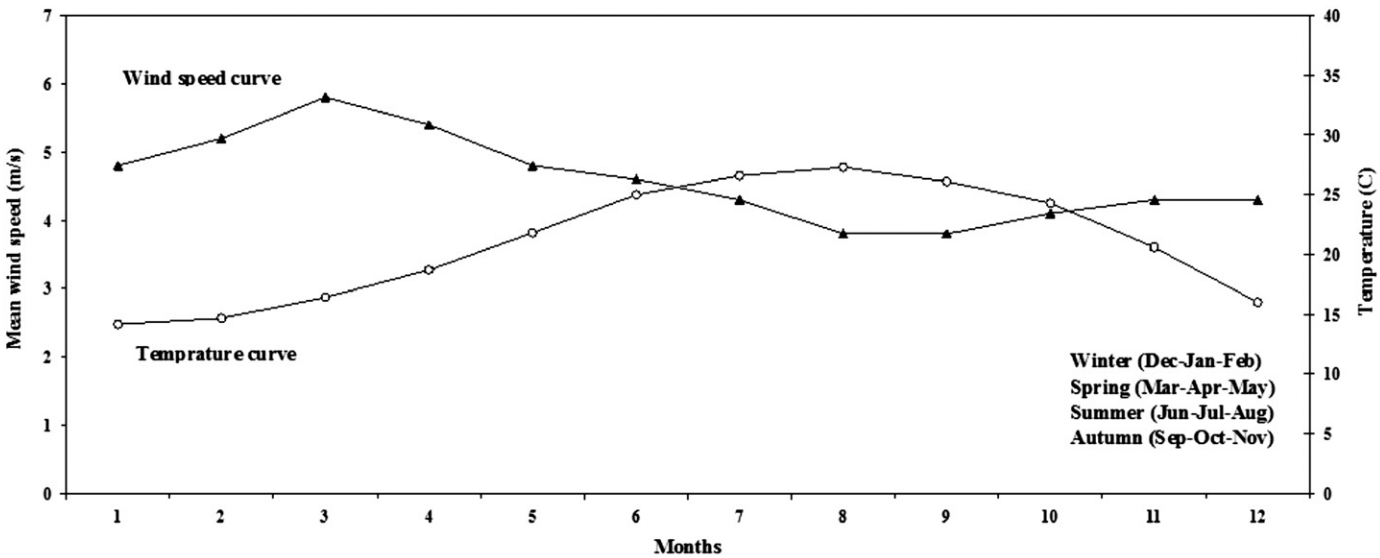

Fig. 4. Monthly variation of wind speeds and air temperature at 19 m height for Port Said station.

the recorded and published data does not reflect the calibration factor. It was also necessary to adjust the wind speed data to a height of 10 m in order to make it directly related to the objective of those people working in the renewable energy sector [24,25].

Over the last decades the effect of different heights on wind speed has been studied by many authors [26–28], and the relationship for computing the wind speed at a height of 10 m when measurements are taken at heights other than the standard 10 m is given as

$$V_1 = V_2\left(\frac{H_1}{H_2}\right)^{\alpha} \tag{1}$$

where V_1 is the estimated mean wind speed at 10 m height, V_2 is the mean wind speed measured by the Renewable Energy Authority, Egypt, at Port Said station, H_1 is the anemometer height, 10 m, H_2 is the anemometer height at Port Said station.

Recently, α is the roughness factor, this parameter is the wind speed power law index, which is considered to be 1/7 or 0.14, for surfaces with low roughness, as given by the one-seventh power law. In addition, the value of α in Eq. (1) depends on the time of the day, the wind speed level, the wind stability and the surface roughness. This value varies from 0.10 to 0.40.

The simply computed roughness factor, α, which results from the wind speed measurements, recommended by many authors was used as follows [29]:

$$\alpha = \frac{0.37-0.0881\ \ln V_2}{1-0.0881\ \ln(H_2/10)} \tag{2}$$

In order to evaluate the wind energy potential of any site, it is important to drive the expected probability distribution of the site's wind speed. Regarding this aspect much attention has been given to the Weibull function, which is characterized by two parameters and gives a good match with experimental data according to Darwish and Sayigh [30]. It is well known that most wind speed data in the moderate–high wind speed range can be represented by the cumulative probability of the Weibull distribution [31], for which

$$F(v) = 1-\exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{3}$$

where $F(v)$ is the cumulative probability that the mean wind speed is less than v, c is a reference wind speed (scale parameter), and k is a shape factor.

Also, earlier studies [32] have determined that a general trend exists between Weibull k values (or variance of the wind distribution) and the mean wind speed. Mathematically results can be expressed for average, high (90 percentile), and low (10 percentile) variability sites by

$$k = \left| \begin{array}{ll} 5{V_m}^{0.5} & \text{(low)} \\ 0.94{V_m}^{0.5} & \text{(average)} \\ 3{V_m}^{0.5} & \text{(high)} \end{array} \right. \tag{4}$$

Recently, the following equations are recommended for the applications:

$$k = 0.94{V_m}^{0.5} \quad \text{for } V_m \approx (3-5)\ \text{m/s at 10 m hub height} \tag{5}$$

$$V_m = c\Gamma(1+k^{-1}) \tag{6}$$

Wind is merely air in motion. The air has mass – though its density is low – and when this mass has velocity the resulting wind has kinetic energy. Thus, the available power of the wind per unit area is estimated by

$$\mathbf{P}_{wind} = \frac{1}{2}\rho {V_m}^3 \ \ (\text{W/m}^2) \tag{7}$$

where ρ is the standard air density (ρ=1.225 kg/m^3 dry air at 1 atm and 15 °C), V_m is the monthly mean wind speed (m/s).

In case of an ideal turbine, power output is influenced due to change in temperature and pressure. So, the corrected monthly air density $\overline{\rho}$ (kg/m^3) is expressed as [33]

$$\overline{\rho} = \frac{\overline{P}}{R_d\overline{T}} \tag{8}$$

where $\overline{P}$ is the monthly mean air pressure (N/m^2), $\overline{T}$ is the monthly mean air temperature in Kelvin (°C+273), and R_d is the specific gas constant for air (R_d=287 J/kg K).

Then the corrected power, available in wind at the standard height 10 m, can be calculated as follows:

$$\mathbf{P}_{10} = \frac{1}{2}\overline{\rho} {V_m}^3 \ \ (\text{W/m}^2) \tag{9}$$

In addition, for calculating the mean power density over a long time T for one month. If we take 30 days per month we end up with the following equation, where the available mean power for a height less

than 100 m, above the ground level per month can be expressed as

$$\mathbf{P}_{h(mo)} = 0.36\,\overline{\rho} V_m{}^3 \left(\frac{\mathrm{h}}{10}\right)^{3\alpha} \quad (\mathrm{kW/m^2\ month}) \tag{10}$$

where α is the roughness factor, usually in the range $0.05 \le \alpha \le 0.5$. In this analysis, $\alpha = 0.25$ is the corrected roughness factor for Port Said region.

4. Result and discussion

4.1. Monthly and seasonal Weibull parameters

The Weibull distribution (named after the Swedish physicist W. Weibull, who applied it when studying material strength in tension and fatigue in the 1930s) has been used to represent wind speed distributions for application in wind loads studies for some time and it can give a good fit to experimental data. Firstly, by applying the available wind data for the station under study at 19 m height with Eq. (2), it is evident that the corrected roughness factor for Port Said region has been found to be $\alpha = 0.25$. So, the variation of the wind speed with elevation for this site was introduced, both monthly and annually for the heights of 10 and 50 m in the wind observation station. Obtained results are presented in Table 3. Annual mean wind speed at the 50 m height is determined as 5.8 m/s while the maximum mean wind speed was 7.3 m/s in March.

Thus, Eqs. (5) and (6) were applied to obtain the monthly and seasonal values of Weibull parameters *k* and *c* with the height of 10 m above the ground level for Port Said station. The results are shown in Tables 3 and 4. When using these values for hub height, *k* may be assumed to be unaffected by height, and the scale parameter *c* may be estimated from the usual power law which generally holds up to a height of 100–150 m [34].

From Tables 5 and 6 we can derive the following:

(1) The range of *k* is between 1.68 and 2.02, where the shape parameters tend to be higher from January to June during the year.
(2) The highest *c* value is 5.5 m/s in March and the lowest is found 3.6 m/s in August and September.
(3) The long-term seasonal *k* and *c* values are highlighted in Table 5. In general, values of the scale parameter are low throughout both (winter–autumn) seasons and high during the spring and summer periods.
(4) For large values of *k* at Spring season, the majority of the wind speed data tend to fall around the mean wind speed and then the mean wind speed at this season is high ($v_{Spring} = 4.5$ m/s). Hence, the wind is sufficient during the ***fourth*** of the year at Port Said City for high power generation.

4.2. Evaluation of air density and wind power density

Mayhoub and Azzam [17], concluded that, for Egypt it is not preferable to estimate wind power values by using a Weibull distribution. The wind power estimation is based on a simple model, where the total theoretical mechanical power available in a given air stream is equal to the volumetric rate times the kinetic energy per unit volume of air stream. This is expressed in Eq. (7). By applying the measured wind data for Port Said station (monthly average air temperature, mean monthly of air pressure) with Eqs. (7)–(10), the values of corrected monthly air density $\overline{\rho}$, corrected monthly wind power $\mathbf{P}_{10}$ at a height of 10 m and the monthly wind power available $\mathbf{P}_{50}$ at hub height 50 m during the

Table 4
Monthly long-term shape parameter, *k*, and scale parameter, *c*, at 10 m hub height.

Month	*k*	*c* (m/s)
January	1.90	4.6
February	1.97	5.0
March	5.8	5.5
April	2.02	5.2
May	1.90	4.6
June	1.86	4.4
July	1.81	4.2
August	1.68	3.6
September	1.68	3.6
October	1.76	3.9
November	1.81	4.2
December	1.81	4.2
Annual mean	1.86	4.4

Table 5
Seasonal long-term shape parameter, *k*, and scale parameter, *c*, for Port Said station.

Period	*k*	*c*
Winter	1.84	3.3
Spring	2.02	5.2
Summer	1.86	4.4
Autumn	1.71	3.7

Table 6
Monthly corrected air density, and corrected and available wind power at 10 and 50 m hub heights, respectively, apart from the observed values of air temperature and pressure for Port Said station.

Month	*T* (°C)	$P \times 10^2$ (N/m²)	$\overline{\rho}$ (kg/m³)	$\mathbf{P}_{10}$ (W/m²)	$\mathbf{P}_{50}$ (kW/m² month)
January	14.2	1017.3	1.23	42	101
February	14.7	1016.0	1.23	52	125
March	16.4	1015.1	1.22	72	173
April	18.7	1013.4	1.21	59	142
May	21.8	1012.4	1.20	41	99
June	25.0	1010.7	1.18	35	84
July	26.6	1007.5	1.17	30	72
August	27.3	1008.1	1.17	19	46
September	26.1	1011.7	1.18	19	46
October	24.3	1014.7	1.19	26	63
November	20.6	1016.2	1.21	31	75
December	16.0	1017.2	1.23	31	75
Annual	21.1	1013.4	1.20	38	92

Table 3
Estimated monthly and annual mean wind speed (m/s) at 10 and 50 m heights above the ground level in this site.

Mean wind speed	Month												Annual mean
	January	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*September*	*October*	*November*	*December*	
V_{10}	4.1	4.4	4.9	4.6	4.1	3.9	3.7	3.2	3.2	3.5	3.7	3.7	3.9
V_{50}	6.1	6.6	7.3	6.9	6.1	5.8	5.5	4.8	4.8	5.2	5.5	5.5	5.8

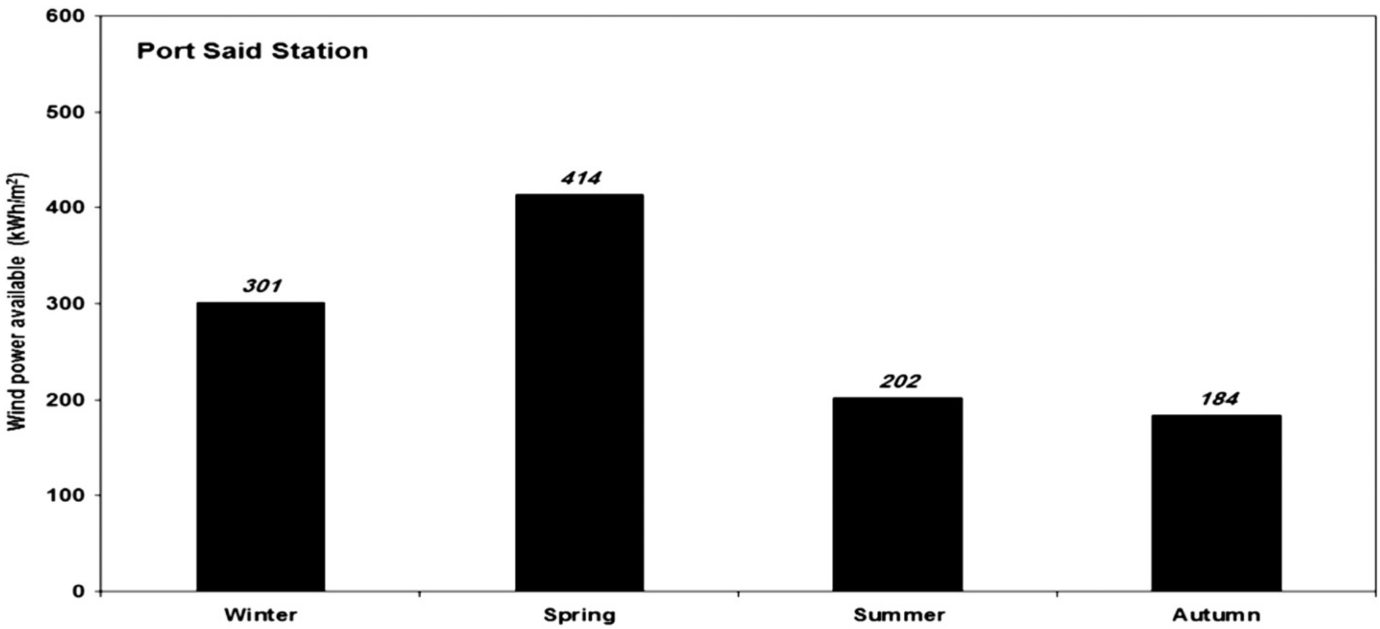

Fig. 5. Seasonal averages of available wind power during the year at 50 m hub height.

year were calculated and listed in Table 6. The results of $\mathbf{P}_{50}$ are shown in Fig. 5. From these tables and figures, we found that

(1) The obtained values of corrected monthly air density are almost stable and the shift from the standard air density ($\rho = 1.225$ kg/m^3) is very small. This confirms the stability of the atmosphere at Port Said region throughout the year.
(2) The absolute maximum highest wind power, $\mathbf{P}_{50}$, was recorded in March as 173 kW/m^2 and the absolute minimum of $\mathbf{P}_{50}$ was found to be 75 kW/m^2 in November and December.
(3) In addition, in Fig. 5, the highest value of the mean power density for the Spring season is 414 kW/m^2, followed by 301 kW/m^2 in Winter months and then followed by 202 kW/m^2 in the Summer period for actual data. Hence, the power density available during the *almost* the year at Port Said station is ideal for electricity generation with installations of medium size wind turbines (150–600 kW).

5. Conclusions

As seen from the results of the present analysis, the research has led to the following:

(1) The wind in Port Said City are predominantly northerly throughout the year. So, north seems to be the only wind direction to be considered in the wind farm project, which will be developed in the campus area.
(2) Annual mean wind speed for this site is ranging from 4.6 to 5.8 m/s at the heights of 19–50 m, where the minimum required wind speed for a wind park (at 20 m height) is about 3 m/s which is equivalent to 2.54 m/s at 10 m height, a typical turbine will operate about 75–80% of all the time throughout the year [23].
(5) For the investigated station with Weibull parameters *k* and *c*, see Tables 3 and 4, we can derive that the wind is sufficient during the *fourth* of the year at Port Said City for high power generation.
(3) The monthly corrected values of air density, see Table 6, is lightly smaller than the standard air density $\rho = 1.225$ kg/m^3. This confirms the stability of the atmosphere at Port Said region during the year and therefore, it causes an improvement in the efficiency of wind turbines that worked at this site.
(4) Investigation of available power density at the height of 50 m indicates that, the power density available during the *almost* the year at Port Said station is ideal for electricity generation with installations of medium size wind turbines (150–600 kW).

This preliminary study could be considered as the basis for further research and development of the wind technology applications in the coastal location Port Said City at Suez Canal–Mediterranean intercept in the near future.

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